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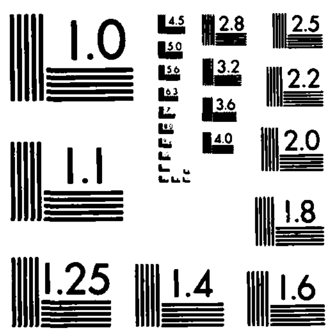

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Two Global Positioning System (GPS) receivers were used to simultaneously track GPS satellites on a very long baseline. The baseline was 8344 km and subtended an earth-centered arc of about 85°. Due to the large distance separating the antennas and their location in the Southern Hemisphere, only two satellites of the present GPS constellation were able to be tracked simultaneously at both sites. The receiver antennas were placed over position markers with known absolute position accuracies of about 1 to 2 m. Doppler

20. ABSTRACT (Continued)

data and the satellite broadcast ephemerides were collected at both sites for a period of about a month. Weekly and daily estimates of the relative antenna positions were determined. The data were processed using linear least-squares procedures, which held one site fixed and estimated corrections to the assumed coordinates of the second. The baseline length was established with an error of less than 1 part per million (ppm).

FOREWORD

The development of the NAVSTAR Geodetic Receiver System (NGRS) was funded by the Defense Mapping Agency (DMA) as a means to demonstrate the capability of using the Global Positioning System (GPS) transmissions to achieve high-accuracy geodetic positioning. The receiver was designed by Stanford Telecommunications Incorporated. The supporting hardware and the system microprocessor controller software were proposed and implemented at the Naval Surface Weapons Center (NSWC) by the Advanced Projects Division, Electronics Systems Department. Data reduction was performed by the Space Flight Sciences Branch of the Space and Surface Systems Division, Strategic Systems Department. Operators for the equipment at the two sites were provided by the sponsor through the Defense Mapping Agency Hydrographic/Topographic Center, Washington, D.C.

Approved by:

O. F. BRAXTON, Head
Strategic Systems Department

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CONTENTS

	Page
INTRODUCTION	1
FORMULATION FOR PROCEDURE 1	2
FORMULATION FOR PROCEDURE 2	3
TEST RESULTS	5
TRAJECTORY ACCURACY	8
CONCLUSIONS	9
REFERENCES	10
DISTRIBUTION	(1)

INTRODUCTION

The Naval Surface Weapons Center (NSWC) has developed two NAVSTAR Geodetic Receiver Systems (NGRSs) utilizing Stanford Telecommunication Inc. (STI) Global Positioning System (GPS) receivers. The first NGRS was operational in February 1979, and, during the course of that year, gathered data at several sites in the United States. Throughout 1980, the first system was progressively modified so that it and the second system, developed during that year, had as much common hardware and software as practical. Both systems accurately measure the biased Doppler ranges on both L1 (1575 MHz) and L2 (1227 MHz) channels at 1-min intervals. These measurements are received from one satellite at a time, and satellites are changed sequentially in accordance with a predefined schedule.

During January 1981, both NGRSs were operated side by side at Dahlgren, Virginia. The two NGRSs were connected in several configurations, including being connected to the same or separate clocks and the same or separate antennas. As reported in Reference 1, the phase measurement accuracy of the two receivers, when operated with a common frequency standard, was found to be 1.3 cm RMS for the biased vacuum range. This is the measurement accuracy after the ionospheric correction has been applied. For the common antenna configuration, the relative positioning estimates were under 10 cm in error when using a common clock and under 50 cm when using separate clocks. Both receiver systems used the same model Hewlett-Packard, high-performance, Cesium frequency standard. Reference 1 provides additional information about the equipment that comprises the NGRS.

In September 1980, the first receiver, NGRS1, was used with two similar systems, developed elsewhere, to estimate relative antenna position on 25- to 50-km baselines. The accuracies were reported in Reference 2 to be about 1 m, or about 20 ppm. Much of this error was attributed to clock inaccuracies.

This report demonstrates the capability of the current GPS constellation and broadcast ephemeris to determine relative antenna positions over a very long baseline. One of the two systems (NGRS1) was located at Mahe in the Seychelle Islands off the east coast of Africa. The NGRS2 was located at Smithfield near Adelaide, Australia. Figure 1 is a plot of the two station locations and ground tracks of the two satellites that could be observed simultaneously from the two sites. The points plotted are for each 10 min of the pass.

These two sites are active TRANET stations whose absolute coordinates are known to within the survey accuracy available from the TRANSIT satellite system. Given an error of 1.5 m in these positions, the baseline should be known to within 0.3 ppm. The results of processing the GPS data showed that it is currently capable of producing accuracies better than 1 ppm, on this baseline, but not better than the given 0.3 ppm.

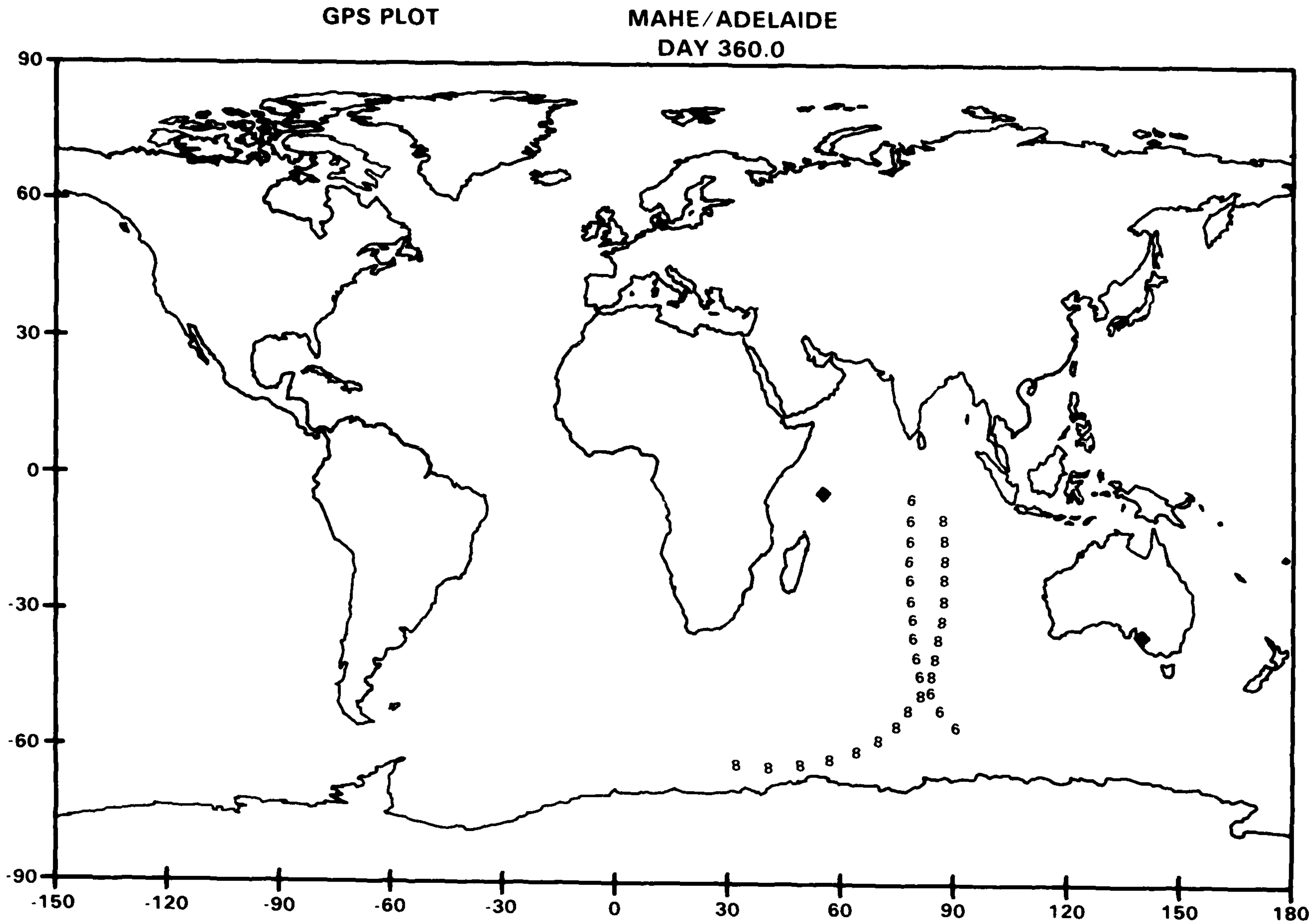

FIGURE 1. GROUND PLOT OF GPS SATELLITES TRACKED BY BOTH SEYCHELLES AND AUSTRALIAN SITES

Two similar methods were used to determine relative antenna position. Both are linear least-squares procedures that hold the Australian site fixed and estimate corrections to the assumed position of the Seychelles Islands' site. The first procedure, which uses the difference in simultaneously observed biased ranges at each site as its measurements, is denoted as P1 and is described in FORMULATION FOR PROCEDURE 1. The second procedure, P2, uses simultaneously observed range rates as its measurements and is described in FORMULATION FOR PROCEDURE 2. The results of both procedures are presented in the TEST RESULTS section and discussed in the CONCLUSION.

FORMULATION FOR PROCEDURE 1

The formulation for Procedure 1 (P1) was presented in Reference 1 and for convenience is briefly reviewed again. The measurement is the difference between the simultaneously observed biased Doppler ranges at each site. The data from the NGRS consists of continuous Doppler counts read out each minute. These counts are accumulated to achieve precise biased range observations over several hours, or until receiver carrier lock onto the satellite signal is interrupted. This data class has a much lower inherit noise level than conventional pseudorange. In this context, biased Doppler range can be described as a biased range obtained by adding consecutive range differences that are, in turn, obtained from continuous count integrated Doppler observations.

If $\rho_o(t_T, t_H)$ is the observed biased Doppler range transmitted from the satellite at time t_T and received at t_H at site H and τ_H is the transmission time, then the data for the differential correction between sites H and G is

$$\Delta = \rho_o(t_H-\tau_H, t_H) - \rho_c(t_H-\tau_H, t_H) - \rho_o(t_G-\tau_G, t_G) + \rho_c(t_G-\tau_G, t_G) \quad (1)$$

In Equation (1), ρ_c is the corresponding calculated range determined from the GPS broadcast ephemeris, the assumed site location, and the propagation correction factors. A tropospheric correction is applied to the calculated range using the Hopfield tropospheric model. The first procedure does not employ a state element to scale the magnitude of the Hopfield correction, whereas the second procedure does.

For this experiment, the received signal epochs were nearly the same, that is, very close to the even minute. It is assumed that the clock and orbit errors do not change significantly over the small difference in transmission times. This means that the satellite clock errors and some of the orbit errors, depending on the distance between sites, are cancelled. The data are incorporated into a five-state, least-squares estimator, which estimates a linear correction in the North, East, and vertical directions to the assumed position of the Seychelles site, clock drift difference between each site, and the difference in range bias for each data interval. The first procedure assumed the position of the Seychelles site to be 10 m North of its surveyed location. This checks that the estimator is correcting in the proper direction.

The first procedure edited the data according to three criteria. Data with elevation angles of less than 20° were deleted in order to minimize atmospheric correction errors. A plot of the elevation and azimuth angles of each satellite as seen from both sites is presented in Figure 2. In this figure, simultaneous observations begin at point A and end at point B. Data whose Δ of Equation (1) differed from the Δ at the previous time epoch by more than 0.5 m were deleted. Also, if the consecutive good data did not consist of at least 20 points or 20 min, the interval was deleted. This was done to ensure reliable estimates of the range biases.

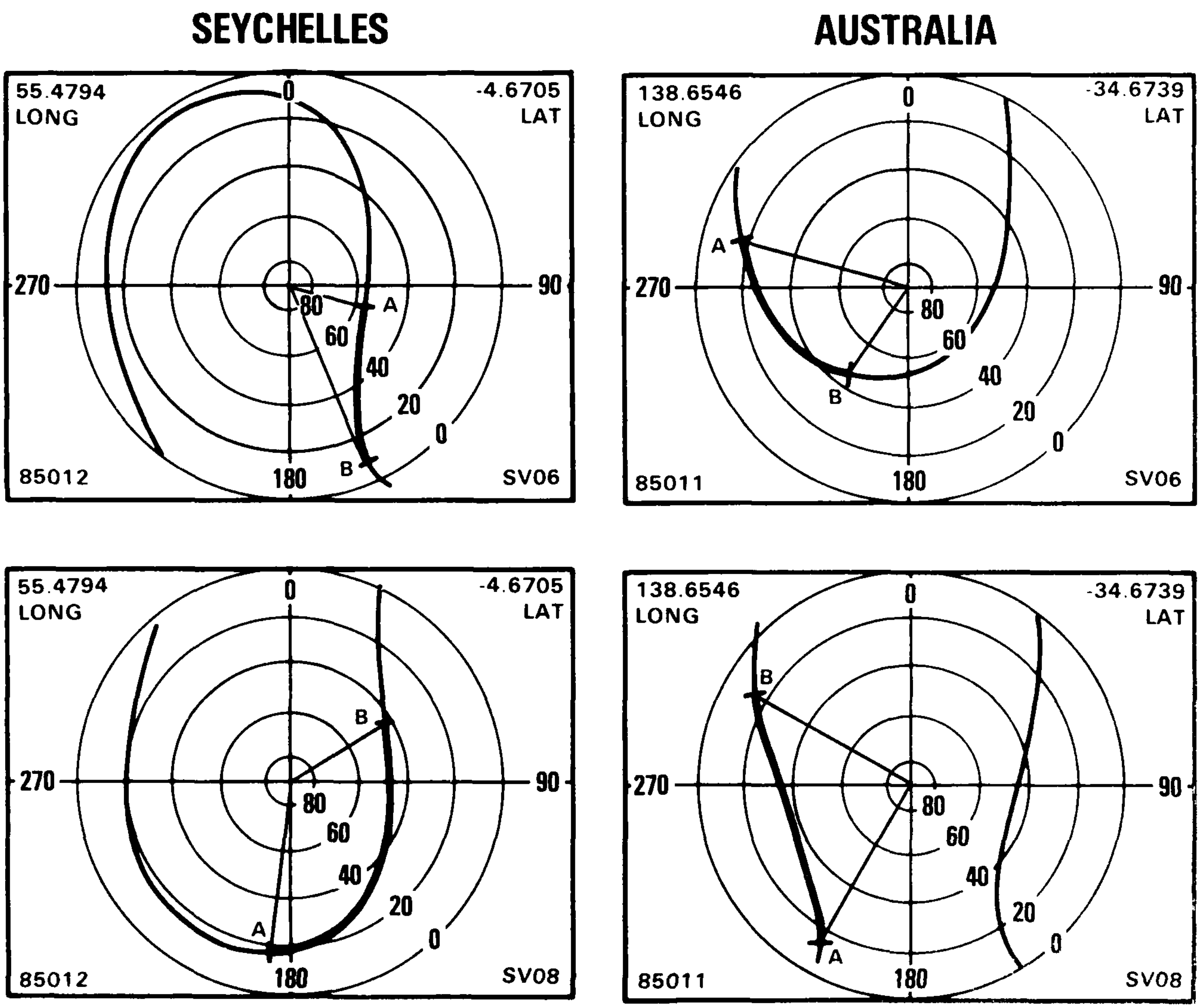

FIGURE 2. AZIMUTH AND ELEVATION ANGLES

FORMULATION FOR PROCEDURE 2

Biased range observations from a single satellite obtained simultaneously at two sites can be differenced to produce a data class that eliminates the satellite frequency standard fluctuations from the problem. This is done in the first procedure described in the previous section. Pairs of these first differences, separated in time by T seconds, may also be differenced. These second differences make up a data class that are independent of the local time bias as well as the satellite biases. The sole clock parameter remaining after second differencing is the difference in time drift between the two local clocks. Effectively, the measurement for P2 is the difference in simultaneous range rates at each site.

Let $\rho_G(t_T,t_G)$ represent a biased range observation transmitte from a satellite at t_T and received at site G at t_G. The first differenc between two sites H and G, can be expressed by

$$\Delta_{HG} = \rho_H(t_T,t_H) - \rho_G(t_T,t_G) \tag{2}$$

The time of transmission t_T is the same for each biased range, but the time of reception will, in general, be different at the two sites. Differencing a pair of these first differences, one at t_{T1} and one at t_{T2}, results in a second difference over a time span $t_{T2}-t_{T1}$

$$\Delta^2_{HG} = \rho_H(t_T\ ,t_H\ ) - \rho_G(t_T\ ,t_G\ ) - \rho_G(t_T\ ,t_H\ ) + \rho_G(t_T\ ,t_G\ ) \tag{3}$$

This can be rearranged so that the biased ranges from one site are grouped together.

$$\Delta^2_{HG} = \rho_H(t_T\ ,t_H\ ) - \rho_H(t_T\ ,t_H\ ) - \rho_G(t_T\ ,t_G\ ) + \rho_G(t_T\ ,t_G\ ) \tag{4}$$

In this form, Δ^2_{HG} is just the difference between conventional single station range difference observations evaluated at reception times equal to the transmission time plus the anticipated propagation time τ. This propagation time is obtained from the predicted satellite position at t_T and reasonable knowledge of the two site coordinates. With this information, τ can be computed.

$$\tau = \frac{1}{c} \left| \bar{r}_s - \bar{r}_G \right|$$

$$t_G = t_T + \tau$$

$\bar{r}_s$ is the satellite position vector at t_T

$\bar{r}_G$ is the site position vector at t_G

In the case of GPS satellites, the slant velocity is less than 1000 m/sec, therefore errors in τ of a microsecond or less can be tolerated in the evaluation of $\bar{r}_s$ and in the range difference:

$$\rho(t_{Ti}, t_{xi}) - \rho(t_{Ti-1}, t_{xi-1}) \quad x \equiv H \text{ or } G$$

For the purposes of this report, the required range differences were obtained from correlated 1-min Doppler data. A 10-min span, consisting of 11 Doppler observations, was fit by a third-degree polynomial. This polynomial was then evaluated at the required times to construct the observed range difference. This operation was performed on data from both sites and the results differenced to obtain one double difference Δ^2_{HG}. One double difference from each 10-min segment of simultaneous observations of SV6 or SV8 were incorporated into a conventional five-state, least-squares estimation algorithm to achieve the final baseline estimate.

The formulation uses the broadcast satellite ephemeris and satellite clock corrections plus absolute position estimates for the two sites. The baseline connecting the sites is computed, and corrections to this assumed baseline vector are the first three states in the solution. A version of the Hopfield troposphere model is used to correct for the tropospheric refraction at both sites. A single-scaling parameter $(1+C_R)$, where C_R is a state element, multiplies the computed Hopfield correction. The difference between the two local clock drifts is the fifth-state element.

In some solutions, an additional drift parameter was inserted on a daily basis. Other solutions kept the same parameter for several days running. Comparison of the bias solutions did indicate that the clock drift element changed over the course of several days. However, the effect on the estimate of the baseline was not significant.

TEST RESULTS

A listing of the data used each day by the two estimation procedures described in the previous two sections is given in Table 1. The estimations were done independently, and the amount of data used differs due to different processing procedures. The first procedure (P1) required at least 20 min of continuous data in order to accurately determine the data interval range difference bias. Therefore, the number of minutes given in Table 1 may represent several data intervals. In addition, data below an elevation angle of 20° was deleted. Neither of these restrictions was used by the second procedure (P2). Also, both estimators had different editing procedures.

TABLE 1. INVENTORY OF DATA

		Data Used for P1 (min)		Data Used for P2 (min)	
Year	Day	SV6	SV8	SV6	SV8
1981	360	105	129	137	210
	361	155	78	60	100
	362	77	74	90	175
	363	69	56	107	67
	364	104	41	137	164
	365	78	0	0	0
1982	4	45	99	60	165
	5	103	160	156	228
	6	104	144	136	205
	7	95	154	119	0
	13	92	32	152	129
	14	21	0	80	37
	15	38	0	79	0
	16	57	0	144	139
	17	84	114	135	136
	18	97	96	115	107
	19	90	61	130	85
	20	90	109	137	180
	21	56	0	139	0
	22	0	140	0	193
	23	104	118	146	190
	24	61	60	95	97

The test results for both procedures using four to six days of data are given in Table 2. The relative antenna position estimation errors are given in the East, North, and Vertical directions at the Seychelles location. The corresponding standard deviations of these estimates are also given. These standard deviations are determined from the measurement noise only. For P1, a constant value for the measurement noise was used that was determined experimentally[1] to be about 0.02 m. P2 used a value determined from the residuals of a polynomial fit to the data. Other

errors, such as orbit, atmospheric c -ections, and clock errors, are not included in these standard deviation values. The standard deviations are a function of satellite to antenna geometry and the number or minutes of data. For P1 this varied from 438 to 1111 and for P2 from 1031 to 1614. The magnitude of the estimation errors from the two procedures increased together from 3.8 m for days 360-364 to about 10.3 m for days 018-024. This is a significant difference between the results of these two spans of data. Since the satellite trajectories nearly repeat each day, such a large difference was not expected. Note, the number of data values and the standard deviations, especially for P1, are fairly close. The cause of this difference appears to be due to fluctuations in the accuracy of the broadcast trajectory. As discussed in the next section, the GPS broadcast trajectory for the days 018-024 was replaced point-for-point by a post-fit trajectory obtained at NSWC. This reduced the magnitude of the P1 estimation error from 10.61 m to 5.20 m, which is close to the 5.02 m average of the three previous spans.

TABLE 2. TEST RESULTS USING FOUR TO SIX DAYS OF DATA

	Error				St. Dev.			Clock Drift		Number Data
Days	Magn. (m)	East (m)	North (m)	Vert. (m)	East (m)	North (m)	Vert. (m)	Diff. (mm/sec)	Cr	Points (min)
					Procedure 1 Results					
360-365	3.79	-1.17	3.50	0.87	0.78	0.30	0.92	-0.67	NA	1083
004-007	5.00	-4.01	2.99	0.15	0.82	0.34	0.99	-0.71	NA	753
013-018	6.28	-3.18	4.81	2.36	1.33	0.48	1.32	-0.88	NA	438
018-024	10.61	-7.18	5.08	5.93	0.75	0.28	0.99	-0.82	NA	1111
					Post-Fit Trajectory					
018-024	5.20	-2.20	2.18	4.18	0.75	0.28	0.99	-1.08	NA	1111
					Procedure 2 Results					
360-364	3.81	0.56	3.77	-0.07	1.08	0.46	0.79	-0.64	-0.044	1247
004-008	4.54	-3.32	2.58	1.71	1.06	0.44	0.78	-0.85	-0.035	1069
013-017	4.52	1.51	4.24	0.44	0.91	0.35	0.69	-0.91	-0.010	1031
018-024	10.10	-7.20	6.21	3.42	0.84	0.31	0.63	-0.90	-0.128	1614
All Data	5.52	-2.64	4.71	1.13	0.50	0.21	0.39	NA	-0.055	4961

Daily estimates were determined for the days given in Table 3. The first five days were consecutive while the remaining five days, which crossed over the calendar days, were chosen because they had similar amounts of data. Note that about 4 hr of data was required to obtain a reliable estimate in terms of the measurement noise only. Simulation results[3] indicate that the range rate data of P2 is a weaker data class than the biased range data of P1. Consequently, for the same data the estimation standard deviations of P2 should be larger than those of P1. However, P1 editing eliminated many more data values and broke a number of long passes into several shorter continuous data intervals. There was a significant variation in these

results. However, note again that the estimated errors on days 20-21 and 22-23 are very much correlated as would be the case for a consistent trajectory error.

TABLE 3. DAILY TEST RESULTS

	Error				St. Dev.			Clock Drift		Number Data
Days	Magn. (m)	East (m)	North (m)	Vert. (m)	East (m)	North (m)	Vert. (m)	Diff. (mm/sec)	Cr	Points (min)
					Procedure 1 Results					
360	3.79	-0.93	1.73	3.24	1.68	0.65	1.69	-0.74	NA	234
361	4.62	-0.82	4.52	-0.48	10.61	3.92	10.33	-0.63	NA	128
362	4.12	1.54	3.57	-1.35	5.91	1.51	3.54	-0.66	NA	151
363	4.68	3.04	1.98	2.96	11.59	2.23	4.80	-0.80	NA	125
364	4.53	4.09	0.54	1.86	18.79	3.92	2.43	-0.35	NA	145
4-5	8.49	-7.30	2.76	3.33	3.53	1.82	0.81	-0.89	NA	202
5-6	3.60	-2.16	2.86	-0.33	1.28	1.70	0.54	-0.59	NA	264
6-7	8.92	-7.72	3.76	2.41	1.80	2.17	0.82	-1.03	NA	239
20-21	9.59	-6.62	6.43	2.59	1.80	2.70	0.67	-0.80	NA	208
22-23	10.17	-6.56	6.00	4.93	1.32	1.74	0.55	-0.82	NA	251
					Procedure 2 Results					
360	8.24	-4.45	5.72	3.92	1.70	0.73	1.23	-0.88	-0.146	347
361	8.81	-3.60	7.77	-2.38	6.73	1.53	5.06	-0.41	-0.176	160
362	3.73	1.06	3.47	0.88	3.06	0.99	2.23	-0.72	-0.083	265
363	5.22	2.28	4.59	-0.97	7.66	2.33	6.07	-0.70	-0.168	174
364	1.43	0.37	1.16	0.75	7.15	1.69	5.59	-0.45	0.132	301
4-5	4.85	-2.55	1.42	3.87	1.67	0.67	1.22	-0.93	-0.001	321
5-6	4.65	-3.14	3.24	1.11	1.49	0.81	1.14	-0.69	-0.099	364
6-7	7.24	-5.89	3.80	1.80	2.12	0.79	1.54	-0.97	-0.070	324
20-21	9.30	-4.80	7.91	0.69	1.86	0.80	1.36	-0.77	-0.081	319
22-23	8.19	-3.24	7.38	1.44	1.83	0.74	1.34	-0.76	-0.072	339

The mean and standard deviations for the first three spans of the estimation errors of Table 2 are given in Table 4. The result from days 018-024 is omitted due to the apparent poor ephemeris during this time. The magnitude of the difference between the two estimated means was 2.42 m, mostly in the East direction. The averages of the standard deviations for each component was similar for each estimation procedure at about 1.5 m.

TABLE 4. MEAN AND STANDARD DEVIATIONS OF ESTIMATES

	East (m)	North (m)	Vertical (m)
P1 Mean	-2.74	3.77	1.13
P2 Mean	-0.42	3.53	0.69
P1 Standard Deviation	1.46	0.94	1.13
P2 Standard Deviation	2.56	0.86	0.92

TRAJECTORY ACCURACY

In Table 2 of the previous section, two sets of estimation errors were presented for days 018-024. The first set used the GPS broadcast trajectory. The second set used a post-fit trajectory obtained from monitor station data fitted over the same span. The post-fitted trajectory reduced the magnitude of the estimation error by about 5 m. The accuracy of the broadcast ephemeris was of concern, since the baseline was so long, and the antenna locations were in the Southern Hemisphere while the GPS monitor stations were all in the Northern Hemisphere. This section discusses the sensitivity of the first estimation procedure to trajectory accuracy.

The maximum differences in the calculated ranges for the broadcast and post-fit trajectories is given in Table 5 for both the Australian and the offset Seychelles sites. For the span in question, the maximum difference was 8.19 m for the Australian site and -6.19 m for the offset Seychelles site. More important to the estimation procedure is the change in the difference over the pass and between the two sites. The average difference in calculated ranges over each data interval is also given in the table. This average change varied significantly. The largest average changes were -1.91 and -4.25 m/hr for SV6 at each site and 2.53 and 0.76 m/hr for SV8 at each site. Also, there was fairly large variation between each day. These variations were not modelled by either estimation procedure. Both procedures assumed a constant drift error over the entire span of the data.

The correction partials of the estimation procedure are sensitive to the changes in the error of the calculated range. Also note that the calculated range is subtracted from the observed ranges and the result is differenced between sites to form the measurement data. Here, it must be pointed out that although the post-fit trajectory is not the actual orbit, it is assumed to be closer to the true trajectory than the broadcast ephemeris.

TABLE 5. COMPARISON OF CALCULATED RANGES DETERMINED FROM A GPS BROADCAST TRAJECTORY AND A POST-FIT TRAJECTORY

Record	Satellite	Day	Start Time of Day (sec)	End Time of Day (sec)	Maximum Difference in Calculated Ranges: Australia (m)	Maximum Difference in Calculated Ranges: Seychelles (m)	Average Change in the Difference in Calculated Ranges: Australia (m/hr)	Average Change in the Difference in Calculated Ranges: Seychelles (m/hr)
1	6	18	11580	15960	8.19	-4.72	-1.48	-4.25
2	6	18	16260	17580	6.38	-6.19	-1.91	-3.05
3	6	19	11340	16680	5.41	-3.07	0.10	-1.98
4	6	20	11100	16440	5.96	-3.37	-0.31	-2.57
5	6	21	11700	15000	5.23	-2.68	0.26	-1.85
6	6	21	15360	17040	5.33	-3.41	0.15	-1.22
7	6	23	10380	16560	7.52	-4.72	-0.91	-3.32
8	6	24	10320	13920	-2.03	-1.10	0.18	-1.66
9	8	18	73020	74580	-0.98	0.20	1.13	0.44
10	8	18	76500	80580	-1.49	-0.57	-0.96	-0.65
11	8	19	76740	80340	-1.53	-0.69	-1.40	-0.16
12	8	20	70560	73320	-2.35	-0.46	2.19	0.76
13	8	20	76440	80100	-1.11	-0.42	-1.04	-0.59
14	8	22	70080	74040	-2.62	-0.69	1.96	0.57
15	8	22	75240	79560	-1.08	-0.49	-0.71	-0.38
16	8	23	69840	73860	-3.19	-0.95	2.53	-0.05
17	8	23	74700	77640	0.17	-1.42	0.10	-0.50
18	8	24	75540	79080	1.39	0.46	-0.67	-0.18

CONCLUSIONS

The current relative positioning capability of the GPS has been demonstrated for a very long baseline, nearly a quarter of the circumference of the earth. Using only two GPS satellites, accuracy was better than 1 ppm. Certainly, a future full GPS-satellite constellation would provide a significant improvement to the available satellite to antenna geometries.

It was also demonstrated that for such long baselines, trajectory inaccuracies are a major source of errors in the relative position estimates. Consequently, if future improvements in the satellite ephemerides are realized, the potential exists for a proportional improvement in the positioning capabilities over long baselines. Additionally, receivers that are in development have the capability to track several satellites simultaneously. This ability will reduce the time required on site and also reduce the sensitivity to local clock fluctuations.

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